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MASS DETERMINATION OF THE IONISING PARTICLES RECORDED IN PHOTOGRAPHIC PLATES EXPOSED TO COSMIC RAYS*

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ABSTRACT. This paper contains an account of investigations on cosmic rays at high altitudes with photographic plates. A method for the estimation of the average mass of ionising particles producing single tracks in these plates is described. A discussion on the theoretical basis of the method and its limitations is also given.

INTRODUCTION

§1. Evidences have been obtained by a large number of investigators that some special types of photographic plates, when exposed to cosmic radiation at high altitudes can record tracks due to heavy ionising particles. Many of these are single tracks while others are multiples, consisting of two or more tracks radiating from a single point. The single tracks may be due to either charged primary particles or to charged secondaries produced in the emulsion by the action of some component of the primary rays. The multiple tracks are always due to charged secondaries produced in the material of the emulsion under the action of some component of the cosmic ray. The charged secondaries are usually assumed to be protons, produced by nuclear interactions (nuclear evaporation process) between photon and neutron components of the cosmic rays and atomic nuclei. In addition to these proton tracks, other dense ionisation tracks are found which are attributed to multiple charged particles, eg, α particles, etc.

Since 1939, we have been exposing Ilford halftone plates to cosmic radiation at different altitudes, *viz.*, Darjeeling (7000 ft.); Sandakphu (12,000 ft.) and Pharijong (14,500 ft.). Some were exposed directly to the cosmic rays while others were exposed under different thicknesses of water paraffin and lead. As a result of such absorption experiments some definite information regarding the nature of primary comic radiation can be obtained. These primary penetrating particles are believed to be chiefly protons. These results are in course of publication.

During the examination of these plates, the first thing which struck us was, that some of the tracks were curved. These curvatures were evidently due to multiple scattering in the nuclear fields of different atomic particles in the emulsion.

According to our previous experience with proton, α particle and electron tracks in photographic emulsions, we were convinced that these tracks were

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due to some single charged ionising particle having a mass intermediate between proton and electron. In a communication to 'Nature' (Bose & Chowdhuri, 1941), it was shown that from a knowledge of the mean grain spacing along the track-length and their multiple scattering, the average mass of these particles, found in plates exposed under air, can be estimated ; it was found to be of the same order of magnitude as that assumed for mesotron, *viz.*, about 200 m_0.

The method used by us for the determination of the mass of the particle is a statistical one. The average mass of the ionising particles was found also to depend on the nature of the absorbing substance under which the plates were exposed.

In the present paper we propose to discuss in some detail the assumptions underlying the method used by us to determine the mass of the ionising particles and also the limitations of the method used.

In § 2 we have given a discussion of the theoretical basis of the method which has been used by us to estimate the average mass of the ionising particles.

In § 3 we have collected together all the experimental data regarding single ionisation tracks, which appear in plates exposed to cosmic rays under different conditions, and from which the average mass of these particles were determined.

In § 4 an interpretation of the experimental results is given, and in § 5 we have discussed the limitations of the method employed for the determination of the mass of the charged particles.

§ 2. It is known that the characteristics of the tracks of an ionising particle in a photographic emulsion are (*i*) its range R (*ii*) the mean grain spacing (m.g.s.) along its tracks length R/n-1, where n is the number of silver grains deposited along the track of length R, and (*iii*) the track curvature, which is measured by the angle between the tangents drawn at the end and the beginning of the track.

In a previous paper by Choudhury (1942-43) (we shall denote it as I), the relation which exists between the first two of these quantities, and the initial energy of the ionising particle has been discussed in detail.

Assuming that the energy loss of the charged particle is due to ionisation only, we have used the approximate integration of the ionisation loss equation given by Heitler and Ma (1940).

$$R = \frac{E^2}{2AMz^2 \log . \frac{(aE)}{M}} \qquad \cdots \quad (1)$$

$$E = \tfrac{1}{2}Mv^2 ;$$

where E = kinetic energy of charged particle, whose mass is M & nuclear charge ze.

$A = 2\pi\sigma Z r_0{}^2 mc^4$ $a = 2\sqrt{2}/IZ$; σ = No. of atoms per c.c. of the medium.

Z = nuclear charge.

r_0 = classical electronic radius = e^2/mc^2.

The mean grain spacing along a track, which is inverse to mean grain number, has been taken to vary inversely as the mean ionisation. Since E/R is the mean ionisation,

$$\text{m.g.s.} \sim v^2/4Az^2 \log\left(\frac{av^2}{2}\right) \quad \cdots \quad (2)$$

It follows from the above that if two different kinds of particles like proton and mesotron carrying the same unit charge e and of masses M and μ respectively, have the same m.g.s. along their tracks, then the ratio of their kinetic energies

$$\frac{W_M}{W_\mu} = \frac{M}{\mu}. \quad \cdots \quad (3)$$

The principle of the method used in estimating the mass of the ionising particles recorded in cosmic ray plates thus depends on the determination of the kinetic energies of protons and of the particles observed in cosmic ray plates having the same m.g.s. We have assumed that these particles are singly charged like protons.

(*a*) Determination of the energy of proton :

In paper I, a calibration curve connecting the kinetic energies of protons with the m.g.s. along their track lengths was given. It was shown there that for energies above 4 *m*V, the m.g.s. bears a linear relation to the energy of the protons.

Extrapolating this curve, energies of protons corresponding to different values of m.g.s. can be obtained. In doing so, we have assumed that this linear relation holds good also for higher proton energies. It has yet to be determined how far this linear relation holds good. To judge from the general trend of H & D curves, which Bose (1943), has shown to be roughly of the same nature for the action of photons and of ionising particles on photographic plates, this linearity relation cannot be expected to hold good for very high energy particles.

(*b*) Determination of the kinetic energy of the particles producing single tracks on the photographic plates exposed to cosmic radiation. As stated previously some of the tracks found in cosmic ray plates are curved due to multiple scattering suffered by the particles traversing the medium.

We have applied the theory of multiple scattering, modified to suit our experimental conditions, to determine the average energy of these particles. We have found it useful in this connection to develop an analogy between the mean displacement of a colloidal particle due to its Brownian motion and the mean deflection of the charged particle due to successive deflections by atomic nuclei traversed by it.

Consider the motion of a Brownian particle due to impacts suffered by it during an interval τ.

We fix our attention to the motion of one such particle and suppose that the motion takes place parallel to one direction only. During the interval τ, let there be 'n' number of collisions, which displaces the particle in equal steps of length 'l', which may be at one instant positive and at another negative; n will be considered to be very large. Then the probability that the particle will be displaced $n/2-b$ times in the negative and $n/2+b$ times in the positive directions out of the total n steps will be $\frac{1}{2^n}\frac{n!}{(n/2-b)!(n/2+b)!}$, where b is taken to be small in comparison to $n/2$.

After such n collisions the resultant distance traversed by the particle will be $2\times bl=a$

Now the probability that the particle describes a path between a and $a+da$ will be

$$p(a)da=\frac{2}{\pi s}e^{-\frac{a^2}{\pi s^2}}da \qquad \ldots (4)$$

where $s^2=\frac{2}{\pi}nl^2$; $nl^2=$mean square of 'a' ; $s=\sqrt{\frac{2n}{\pi}}.\,l$ $\qquad \ldots (4a)$

Now consider a particle of charge ze traversing the coulomb fields of N nuclei present per c.c. of the material medium, the thickness of which is t. Let Ze be the charge on each nucleus. The particle experiences Nt deflections from its original trajectory. These deflections can take place in any direction. Then using Rutherford's scattering formula for small nuclear deflections, we find that the probability that a particle of charge ze and energy W travelling through a thickness t, is deflected through an angle between Θ and $\Theta+d\Theta$

is $P(\Theta)d\Theta=2\pi Nt.\left(\frac{Zze^2}{W}\right)\frac{d\Theta}{\Theta^3}$. Where $\Theta<<1$.

Williams (1939) has shown, by considering the effect of shielding of the nuclear field by orbital electrons and of the finite size of the nucleus, that for a system of particles scattered according to the above formula, the average angle of scattering

$$\bar{a}=\left\{3\cdot69+\cdot28\log.\frac{Z^{4/3}.\rho t}{A\beta^2}\right\}\frac{Zze^2}{W}\sqrt{Nt} \qquad \ldots (5)$$

It can be written as $\bar{a}=\sqrt{Nt.\frac{2}{\pi}}.\frac{Zze^2}{W}.C$ $\qquad \ldots (5a)$

Now according to Williams the distribution of the deflections of a charged particle due to scattering in the coulomb fields of different nuclei will follow the Gaussian law.

The probability that the particle will be deflected through an angle a as a result of Nt number of encounters suffered by it in traversing t thickness of medium consisting of N nuclei per c.c. is given by

$$P(\alpha)d\alpha = \frac{2}{\pi\bar{\alpha}} \cdot e^{-\frac{\alpha^2}{\pi\bar{\alpha}^2}} d\alpha. \qquad \ldots \quad (6)$$

where $\bar{\alpha}$ is $\frac{2}{\pi}$ times mean square of α.

$$\bar{\alpha} = \sqrt{\frac{2}{\pi} \cdot Nt.}\quad \Theta_0\ ; \ (cf.\ 4a) \qquad \ldots \quad (7)$$

Θ_0 is considered to be the elementary angle through which the charged particle is deflected at each of its Nt encounters either in $+ve$ or in $-ve$ directions.

Comparing (5*a*) and (7) we find that

$$\Theta_0 = C.\ \frac{Zze^2}{W}.$$

Equation (5) has been deduced on the assumption that the forces between charged particle and the atomic nuclei are entirely of coulombian origin and it holds good for charged particles with different spin value, because the spin term effect can be neglected for small angles of deflection. The effect of shielding of nuclear field by the outer electrons and the finite size of the nucleus has also been considered.

The usual method of applying formula (5) is to select a homogeneous group of charged particles, by means of suitable electric or magnetic lens system, and to find out the average angle of scattering of the particles after passing through a thickness t of matter. Thus knowing $\bar{\alpha}$ and W the formula can be used to determine the charge carried by the scattered particle.

APPLICATION TO THE INVESTIGATION OF PENETRATING COSMIC RAY PARTICLES

Recently two investigators Wilson (1940), and Code (1941), have tried to verify the validity of the Gaussian distribution law for the case of fast cosmic ray particles which have suffered multiple scattering. They have applied Williams' formula to the Wilson chamber tracks of penetrating cosmic ray particles which are scattered by given thicknesses of lead, tungsten, etc. Owing to high energies of the particles, they had to use appreciably large thicknesses of scattering materials, leading to a loss of energy of the particles. To overcome this difficulty they have taken the average value W of the energies measured before and after passing through the seattering material. Further they had to deal with an energy spectrum of the incident particles as all of them were not of the same energy; owing to this difficulty of not getting a number of penetrating particles with the same energy W, they have determined the mean value $\overline{W\alpha}$ rather than $\bar{\alpha}$ for a constant W. And they have used the following modified distribution formula

$$p(w\alpha)d(w\alpha) = \frac{2}{\pi\overline{(w\alpha)}}\ e^{-\frac{(w\alpha)^2}{\pi\overline{(w\alpha)}^2}}\ d(w\alpha) \qquad \ldots \quad (8)$$

In Wilson's investigation, particles of energy range between 2×10^8 to 10^9eV traversing 1 cm. thick lead have been considered. F. Code used 3.8 cm. Tungsten scatterer for particles of average energy 10^9eV. It is found that there are always a certain number of particles which show anomalous scattering. A detailed investigation of such cases is expected to furnish information regarding the non-coulombian interaction forces between the primary particles and atomic nuclei.

APPLICATION TO THE PRESENT INVESTIGATION

In our experiment with photographic plates, we have measured angles of deflections due to multiple scattering for different tracks with different m.g.s., (which is a measure of the energy of the particle) all of which are not of the same lengths.

So in applying Williams' formula to the case of ionising particles observed in photographic plates, we find that the particles considered neither traversed the same thickness t nor were they of the same energy W. It is not possible to select out of them a number of tracks all of the same length t with the same m.g.s. and to use such tracks for the determination of α the average angle to scattering. So we tried to apply the scattering formula in a modified form. Using such method we have determined the mass of ionising particles which are found to be of the order of the mass of mesotron.

Assuming that the angles of deflection due to multiple scattering follows Gaussian distribution law, it can be shown that if we suitably select the conditions of our experiment, so as to make α large, then it follows that under such conditions it is highly probable that the individual values of α will not deviate appreciably from the average value of $\bar{\alpha}$. Under such conditions, the deviation of an observed angle of scattering α from its mean value $\bar{\alpha}$ is

$$\delta = \frac{\alpha - \bar{\alpha}}{\bar{\alpha}} << 1 :$$

at the same time $\alpha - \bar{\alpha} = \delta\bar{\alpha} >> 1$. The probability of occurrence of any angle α is given by [6]

$$P(\alpha)\, d\alpha = P(\bar{\alpha})\, e^{-\frac{\bar{\alpha}}{2}\delta^2}\, d\alpha \qquad \dots (9)$$

When the experimental conditions are so chosen as to satisfy the above relation any value of α obtained will be so near the mean value $\bar{\alpha}$ that we shall obtain satisfactory values for the mass of the scattered particles if in (5) we substitute α for $\bar{\alpha}$. Putting $\bar{\alpha} = \beta . \frac{\sqrt{Nt}}{W}$ we find the conditions required to be satisfied are, large Nt and small W. Since particles with long tracks will start with large values of W, the two conditions are not mutually compatible. To overcome this difficulty we have used the following procedure.

We have proceeded first, to sort out particles with energies lying within certain specified limits. Since the m.g.s. along a track is a measure of the energy of the particle producing it, we have classified them according to their m.g.s. The tracks whose m.g.s. lie within a range of 1μ are put together in each group. Due to differernces in the inclinations of the tracks to the surface of the film the tracks classified in a single group may not have the same length, *i.e.*, they do not traverse the same thickness of emulsion.

So our next procedure is to sum up the lengths of the tracks in each group and also the angles of deflection suffered by these tracks. Thus if m be the number of tracks included in a particular group then the combined length of all the tracks is $t_0 = \sum_1^m t_i$ and the total deflection suffered by the particle of track length t_0 is $\alpha_0 = \sum_1^n \alpha_1$ while the m.g.s. of the combined track will be $\frac{\sum_1^m t_i}{\sum n_i - m}$ where n_i is the number of grains in a track. Now the energy of a particle having the track length t_0 and scattering angle α_0 can be found out by using the formula (5).

In applying the scattering formula we have made another assumption to suit our experimental conditions; since the photographic emulsion is heterogeneous in composition, it is assumed that the actual distribution of different kinds of atoms can be replaced by one kind of atom of mean charge Z and mean atomic weight A.

In equation (5) the atomic number occurs as $\sqrt{Z^2}$ so we have taken the value of Z as the root mean sq. of the atomic numbers of different atoms present in the emulsion, *i.e.*,

$$Z^2 = \frac{\sum Z_k^2 N_k^2}{\sum N_k} \qquad \dots \quad (10)$$

where Z_k is the atomic number of the $_k$th element and N_k is the number of atoms of the element per c.c. of the emulsion. The energies of the proton tracks, having m.g.s. equal to those found for the different groups of particles of unknown nature, can be obtained from the calibration curve given in (I). And the average mass of each group of particles is determined by applying eqn. (3).

§ 3. Experimental data :—

In this section we give in some detail the experimental arrangement used and the results obtained from different plates exposed under different conditions.

Our investigation consists of two parts : In the first part we have dealt with plates exposed under air only at Sandakphu (12,000 ft.) and in the second part of the experiment we have collected the data obtained from different plates kept under layers of different homogeneous materials at Sandakphu and at Pharijong.

(*i*) A number of untreated halftone plates (70 μ thick) were exposed under air at Sandakphu on two different occassions. These plates were kept vertically on their long sides.

After development, when examined we observed a number of long single tracks and many multiple star-like tracks. In this paper we have considered only the single tracks in detail. We measured l the lengths of these tracks in the emulsion their inclination θ to the surface of the film, the mean grain spacing along each track and the angles of the deflection due to multiple scattering. The actual lengths of these tracks $l/\cos\theta$ were calculated. The number of tracks per sq. cm. were also counted. All these data are given in Table I. From which the average mass of different groups of particles was calculated, following the method discussed in the previous section. In addition to the data given in Table I, the following data are also required for the calculation of the mass of the particles :—

Number of atoms per c.c. of the emulsion, $N = 1.4 \times 10^{22}$

Density of the emulsion $\rho = 2.89$.

Root mean sq. charge $\sqrt{Z^2} = 11 \cdot 3$.

All these data are taken from paper I.

TABLE I

Plate	Place	No. of Tracks	Range of m.g.s.	m.g.s.	Σl	$\Sigma\theta$	Energy n Mev.		Mass	Average	No. of Tracks per Cm² per 100 days.
							Energy cal-culated	Energy of Proton.			
A	Sandak-phu 12,000ft.	12	$6\mu \rightarrow 5\mu$	5.7μ	0 15 Cm.	18°30′	2.7 Mv.	22.7 Mv.	221		55
		22	$5\mu \rightarrow 4\mu$	4.3μ	0.24 Cm.	61°	1.05 Mv.	12.5 Mv.	160	214	
		33	$4\mu \rightarrow 3\mu$	3.2μ	0.31 Cm.	120°	0.6 Mv.	4.2 Mv.	263		
B		10	$5\mu \rightarrow 4\mu$	4.1μ	0.11 Cm.	39°30′	1.10 Mv	11.2 Mv.	180	219	
		25	$4\mu \rightarrow 3\mu$	3.3μ	0.103Cm.	60°	.68 Mv.	4.8 Mv.	257		17

Time of exposure of Plate A—150 days.

Time of exposure of Plate B—163 days.

It is to be noted here that plates A and B were not equally sensitive to cosmic radiation ; they belonged to two different batches of plates procured from England at different times.

ii (*a*). Effect of placing a layer of hydrogeneous material above the plates:—

At Sandakphu a number of plates were kept under (1) 20 cm. water in a galvanized iron box, (*ii*) 20 cm. paraffin block. Both of these plates were placed vertically ; on another occasion, a pair of plates was kept at Pharijong in a hut under a thick wooden roof. Data, similar to these collected for the plates exposed to air, were obtained for each of these plates. Average masses of the particles belonging to each group, which are responsible for single tracks on these plates, were calculated. All these data are given in Table II.

TABLE II

Place	Absorbing layer.	Range of m.g.s.	m.g.s.	Σl	$\Sigma\theta$	Energy in Mev.		Mass	Average	No. of Tracks per Cm^2 per 100 days.	Ratio of proton Meson numbers.
						Energy calculated.	Energy of proton.				
Sandak-phu	Water	$5\mu \rightarrow 4\mu$	4.4μ	.105 Cm.	$16°30'$	2.4 Mv.	13.8 Mv.	328	314	30	0.1
	20 Cm.	$4\mu \rightarrow 3\mu$	3.4μ	.23 Cm.	$55°$	1.06 Mv.	6.0 Mv.	355			
12,000 ft.	Paraffin	$5\mu \rightarrow 4\mu$	4.5μ	·05 Cm.	$9°$	3.5 Mv.	14.5 Mv.	440		5	0.2
	20 Cm.	$4\mu \rightarrow 3\mu$	3.45μ	.041 Cm.	$12°$	2.0 Mv	6.2 Mv.	588	514		
Phari-jong	$2\frac{1}{2}$ ft.	$6\mu \rightarrow 5\mu$	5.65μ	.11 Cm.	$12°30'$	3.4 Mv.	22.5 Mv.	276			
	mud and	$5\mu \rightarrow 4\mu$	4.4μ	.08 Cm.	$12°$	3.0 Mv.	13.8 Mv.	386	331	12	.09
14,500 ft.	wood	$4\mu \rightarrow 3\mu$	3.3μ	.20 Cm.	$66°$	0.9 Mv.	5 Mv.	332			

Time of exposure of Sandakphu water plate—202 days.

Time of exposure of Sandakphu paraffin plate—163 days.

Time of exposure of Pharijong plate—209 days.

The plate exposed under water at Sandakphu and plate No. A of Table I were from the same batch. The plates exposed under paraffin and those kept of Pharijong were of the same batch as the plate No. B of Table I. The last column in the above table gives the ratio of proton to mestron which must be present in the ionising particles recorded in these plates, to give the average mass found.

ii (*b*). Effect of placing different thicknesses of lead :—

In their investigations Heitler (1939), and his co-workers noticed that there is an increase in the total number of tracks per unit area when plates were exposed at Jungfraujoch (13,800 ft.) under different thicknesses of lead. The maximum multiplication took place under 1.2 cm. Pb. In our experiment we have placed a number of halftone plates at Sandakphu under different thicknesses lead varying from 0.5 cm. to 5 cm. Pb. We have counted the number of tracks in equal areas of the different plates under each thickness of lead. It was observed that the frequency of tracks per unit area of plate initially increased with the lead thickness. The maximum transition effect was observed at 1·5 cm. Pb. almost coinciding with Rossi's first maximum. Then the frequency of tracks began to fall rapidly to a small value under 5 cm. Pb. Some of these results were discussed in a recent paper by Bose (1942-43). In Table III we have given all the data, from which the average mass of the ionising particles recorded in these plates was calculated. This investigation is being continued.

TABLE III

Time of exposure of lead plates—163 days.

Place	Absorbing layer.	Range of m.g.s.	m.g.s.	Σl	$\Sigma\theta$	Enery in Mv. Energy calculated.	Enery in Mv. Energy of Proton.	Mass	Average	No. of Tracks per cm² 100 days.	Ratio of proton Meson numbers.
Sandakphu 12,000 ft.	0.5 Lead	$6\mu\rightarrow5\mu$	5.46μ	.03 cm.	7°30′	3.1 Mv.	21.5 Mv.	258			
		$5\mu\rightarrow4\mu$	4.2μ	.02 cm.	7°30′	2.15 Mv.	12.0 Mv.	331	331	11.3	.09
		$4\mu\rightarrow3\mu$	3.4μ	.06 cm.	25°	1.25 Mv.	6.0 Mv.	404			
	1 Cm. Lead.	$5\mu\rightarrow4\mu$	4.6μ	.11 cm.	8°	5.35 Mv.	15.3 Mv.	552	515	14	0.2
		$4\mu\rightarrow3\mu$	3.24μ	.071 cm.	27°	1.29 Mv.	4.6 Mv.	478			
	1.5 Cm. Lead.	$5\mu\rightarrow4\mu$	4.3μ	.077 cm.	12°30′	2.85 Mv.	12.3 Mv.	404	607	21.2	0.25
		$4\mu\rightarrow3\mu$	3.52μ	.09 cm.	14°	2.65 Mv.	6.5 Mv.	736			
	2 Cm. Lead.	$5\mu\rightarrow4\mu$	4.4μ	.13 cm.	17°	2.67 Mv.	13.8 Mv.	350	450	21.2	0.17
		$4\mu\rightarrow3\mu$	3.6μ	.09 cm.	27°	1.42 Mv.	4.7 Mv.	552			
	3 Cm. Lead.	$5\mu\rightarrow4\mu$	4.4μ	.06 cm.	11°	2.8 Mv.	13.8 Mv.	380	356	13.2	0.11
		$4\mu\rightarrow3\mu$	3.67μ	.08 cm.	31°	1.44 Mv.	7.9 Mv.	333			
	5 Cm. Lead.	$5\mu\rightarrow4\mu$	4.3μ	.02 cm.	7°30′	2.66 Mv.	12.3 Mv.	400	341	7	0.1
		$4\mu\rightarrow3\mu$	3.4μ	.043 cm.	30°	.92 Mv.	6.0 Mv.	282			

It is interesting to note here that we have also observed a number of very dense tracks in some of the multiple stars. The m.g.s. of these tracks were found to be less than 2.4μ. According to the data given in paper I such tracks are due to α- and other multiple charged particles. Single dense tracks were also found. It is not possible to sort out from amongst such dense single tracks those due to α- particles from radio active contaminations from the others produced by the action of the radiations incident on the photographic plates from outside. These tracks have not been included in Table III.

§ 4. DISCUSSION OF THE EXPERIMENTAL RESULTS

Considering Table I, we find that the average masses of the particles are of the order of mesotron mass. We, therefore, conclude that a large number of slow mesotrons of energy 10^6eV have been recorded in these plates exposed to air at Sandakphu. Further, our records show that in these plates the percentage of protons of energy 10^7eV, which can produce tracks with the same m.g.s. as slow mesotrons, is very small. It is also found that the average mass of ionising particles observed in photographic plates kept under hydrogeneous substances is much greater than mesotron mass. It varies from one and half to two times the mesotron mass.

The method, which we are following here for the determination of the mass of the ionising particles, can give only the average mass of the particles. So if in these plates protons are present in comparatively large numbers than those found in the plates exposed to air, then there is a great probability that these also be included in different groups along with mesotrons. Thus the higher value of the mass of ionising particles gives a direct evidence that the plates exposed under this special condition have recorded a large number of protons of energy varying from 10^6eV to 10^7eV. We consider that this increase in the number of proton tracks is due to the fact that the penetrating part of the primary cosmic rays, consisting of fast neutrons and protons, traversing the hydrogeneous matters produce many recoil protons of energy of the order of 10^7eV. These are recorded in the photographic plates and go to increase the average mass of the particles measured.

Further Table II shows that the frequency of tracks per unit area of these plates becomes smaller in comparison to that observed in the plates exposed to air at the same altitude (Table I). This also shows that a part of the primary component of cosmic ray is largely absorbed in hydrogeneous substances ; we consider this as a further indication that this part of the primary beam consists of neutrons and protons.

Another interesting information regarding the primary component of cosmic rays at high altitude has been obtained from the data given in Table III. It will be noticed there that the average mass increases gradually with lead thickness, reaching a maximum under 1.5 cm. pb. Then it shows a tendency to decrease with the increase of lead thickness placed above the plates and becomes 1.5 times the value of mesotron mass under 5 cm. pb. This also shows a transition effect under lead with a maximum at 1.5 cm. pb. Thus we see that there is a close relation between the average mass value of the secondary particles and the multiplication effect of the primary radiation in lead.

Such transition effect is now generally accepted to be due to the multiplication of the soft component of cosmic rays by cascade process. We suppose that this soft component which is produced due to multiplication in lead is responsible for the creation of protons and mesotrons, in the respective energy range for which the photographic plates are sensitive to these rays. These are produced in the lead absorbers placed above the plates or in the emulsion of the plates. It is probable that the protons, observed in these plates whose number shows a maximum under 1.5 cm. pb, are mainly produced by those soft secondaries which have energy of the order of critical energy in lead, *i.e.*, 7×10^6eV.

By considering the ratio of proton/mes otron, we are convinced that in all of these plates mesotrons are also produced in large numbers.

A little consideration of the data given in Table III will show that the increase in the number of particles recorded per unit area of the plate under two different thicknesses of lead, *e.g.*, under 0.5 and 1.5 cm. respectively, is not due entirely to protons produced by a photo-nuclear process, but a certain number of mesotrons are also produced. There has been a doubling of the number of tracks per unit area, on increasing the lead thickness from 0.5 to 1.5 cm. If all the new tracks were due to protons only, then the calculated value of the average mass would come out to be of the order of $1000\ m_0$, against the measured value of $607\ m_0$.

§ 5. LIMITATION OF THE METHOD

We have seen in §3 that the average mass of the particles producing ionisation tracks in photographic plates exposed to air at Sandakphu, is very near that of the accepted value of mesotron mass. In this section we shall discuss some of the limitations of the method used here, which at present preclude its application as a precision method for mesotron mass determination. The principal theoretical drawbacks of the method are (*i*) the procedure of adding together of the individual track deflections α_i to a resultant α_0 and (*ii*) the substitution of this α_0 for $\bar{\alpha}_0$ in equ. (5), for the determination of the average energy of the ionising particle producing tracks with a certain value of m.g.s. We shall now discuss whether by adding together the characteristics of an increasing number of tracks, the accuracy of the mass determination is correspondingly increased.

We suppose $\nu_1, \nu_2, \nu_3 \ldots\ldots\ldots\ldots \nu_i$ be the number of atoms in the thicknesses $t_1, t_2, t_3 \ldots\ldots\ldots\ldots t_i$ of the scattering medium, and we put $t_0 = \Sigma t_i$; $\nu_0 = \Sigma \nu_i$ and $\alpha_0 = \Sigma \alpha_i$. Further we denote by $\bar{\alpha}_0$ the average angle of scattering of a large number of tracks each of length t_0. In each of the strips the deflection $\alpha_i \sim \nu_i^+ - \nu_i^-$, where ν_i^+ and ν_i^- are the number of positive and negative deflections suffered by the particles, so that $\nu_i = \nu_i^+ + \nu_i^-$ and $\overline{\nu_i^+ - \nu_i^-} = \sqrt{\frac{2}{\pi} \cdot \nu_i}$

In a track of length t_0 which is broken up into m small strips $t_1 \ldots\ldots\ldots t_m$ the total scattering produced is the algebraic sum of the deflections produced in the individual strips, *i.e.*, in some the deflections will be in the positive and in others in the negative direction. But in the procedure followed by us, we add together the absolute values of the deflections produced in the strips $t_1 \ldots\ldots\ldots\ldots t_m$; when the number of strips added together is small, the discrepancy between $\alpha_0 = \Sigma \alpha$; and $\bar{\alpha}_0$ will not be large ; on the other hand when the deflection due to a large number of strips is added together, the value of α_0 increases monotonously with t_0 while $\bar{\alpha}_0$ will increase with $\sqrt{t_0}$. After a certain thickness t_0 has been reached, the value of α_0 will be always greater than $\bar{\alpha}_0$. Since the value of W and ultimately of the mass of ionising particle depends inversely on $\bar{\alpha}$, we expect that for larger values of t_0, when α_0 becomes greater than $\bar{\alpha}_0$, the calculated values of the mass of ionising particle will diminish.

We illustrate the correctness of our deduction by the following example. We have already obtained estimates of the mass of the ionising particle from the data obtained from two plates A & B exposed to air at Sandakphu. In Table IV we have given the masses calculated from the two plates separately with tracks grouped together under defined limits and also the same have been calculated when the tracks belonging to the same m.g.s. groups in the two plates have been combined together. It will be seen that mass determined from the combined data always comes out smaller than the masses estimated from the separate data.

TABLE IV

	No. of tracks in			Mass calculated from		
m.g.s.	Plate A	Plate B	Plates A+B	Plate A	Plate B	Plates A + B
$6\mu \rightarrow 5\mu$	12 (0.15 cm.)	2 (.02 cm.)	14 (0.17 cm)	221	not calculated	193
$5\mu \rightarrow 4\mu$	22 (0.24 cm.)	10 (0 11 cm.)	32 (0.35 cm.)	160	180	130
$4\mu \rightarrow 3\mu$	33 (0.31 cm.)	15 (0.10 cm.)	48 (0.41 cm.)	263	250	202

In the columns under tracks number in each row the upper figure represents the number of tracks and lower figure in brackets, their total length in cm.

We propose to send up a large number of plates to Sandakphu to be exposed under air, and we shall find out the value of the average mass of the ionising particles for each group of m.g.s. for each of the plates separately. We shall try to find out whether an empirical criterion can be obtained regarding the grouping up of the tracks within certain m.g.s. limits, which will lead to the most consistent values for the mass determination of the ionising particles. It is also necessary to draw fresh proton energy calibration curves for the plates, using a higher range of proton energy than is available to us at present; probably such plates will be calibrated in future by using higher energy protons and α- particles produced by large cyclotrons.

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SUMMARY

This paper contains an account of investigations on cosmic rays at high altitudes with photographic plates. A method for the estimation of the average mass of ionising particles producing single tracks in these plates is described. A discussion on the theoretical basis of the method and its limitations is also given.

The following results were obtained :

(1) The average mass of the ionising particles producing single tracks on the photographic plates kept exposed to air at Sandakphu approximate to the accepted value for the mass of mesotron. It is found to be 216 m_0. The energy of these particles is of the order of 10^6eV. Protons of energy 10^7eV which produce the same m.g.s. as 10^6eV mesotron are rare.

(2) In the plates exposed under layers of hydrogenous substances (20 cm. water, and paraffin and 2½ ft. wood and mud) the average mass of the particles is found to be about one and half to two times the mesotron mass. It varies from 340 to 514, which indicates the presence of a comparatively larger number of proton tracks. The cause of this effect has been ascribed to the presence of fast primary cosmic ray penetrating particles like neutrons and protons which traversing the hydrogeneous substances produce recoil protons of energy of the order of 10^6eV to 10^7eV. These protons have the same m.g.s. as those due to the mesotron recorded on the plates and thus increase the average mass of the recorded particles.

(3) Photographic plates were exposed at Sandakphu under different thicknesses of lead varying from 0.5 cm. to 5 cm. pb. It is found that the average mass of the particles increases to a maximum value under 1.5 cm. pb and then gradually it comes down to 1.5 times the value of mesotron mass under 5 cm. pb. It is concluded that the soft component of primary radiation undergoes multiplication in traversing the lead plates and the secondaries formed thereby cause the emission of heavy ionising particle either in the lead plates or in the emulsion of the photographic plates.

The secondaries having energy of the order of critical energy, *i.e.*, 7×10^6eV, are probably responsible for the production of protons by some photonuclear process. The ratio of proton-mesotron present in each plate has been calculated. The conclusion is drawn that in the transition layer of lead not only protons but also fresh mesotron are produced.

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